Institute of Applied Physics
Friedrich-Schiller-Universität Jena

activefiber systems

Fiber laser driven high harmonic generation as powerful source for applications

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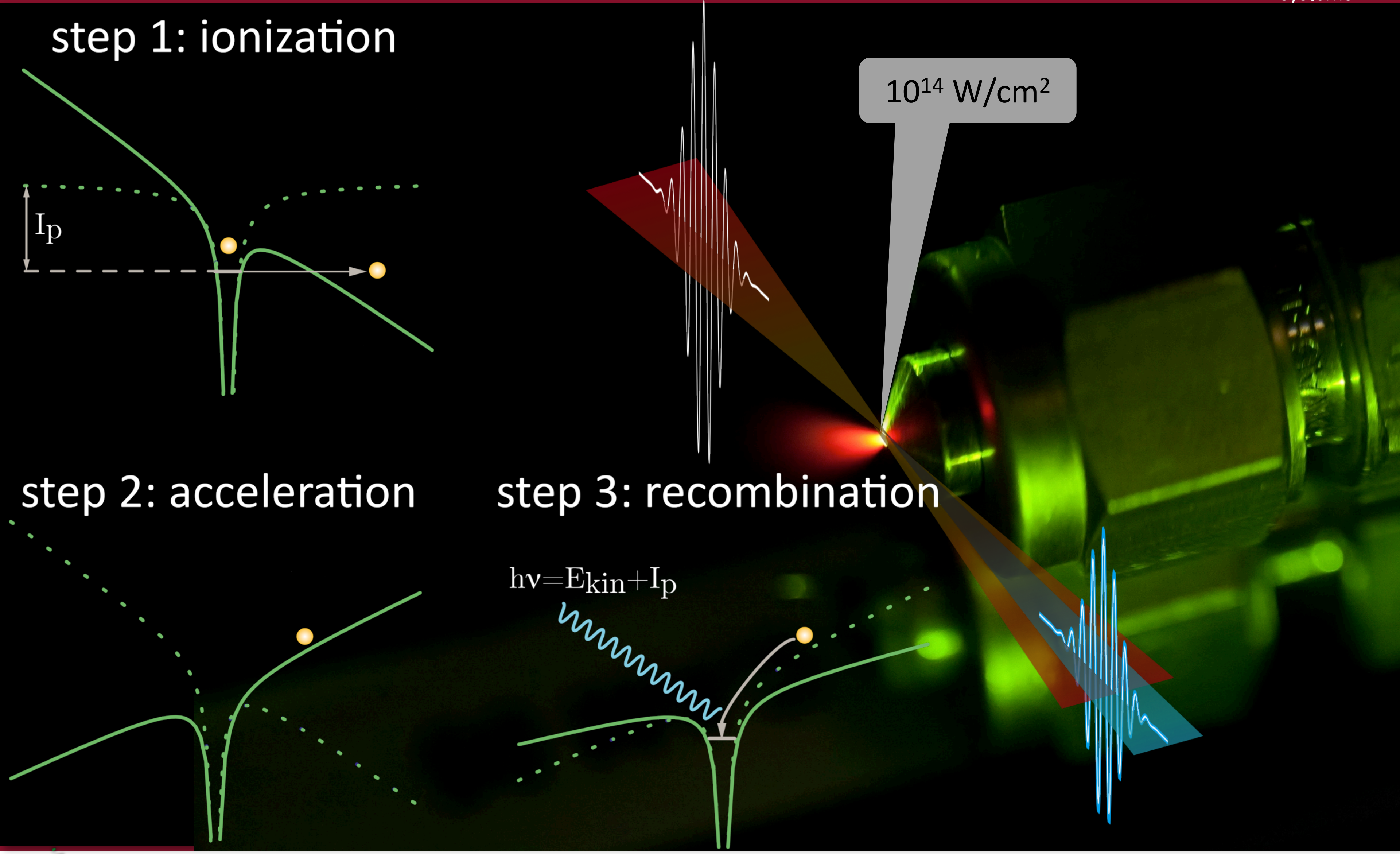
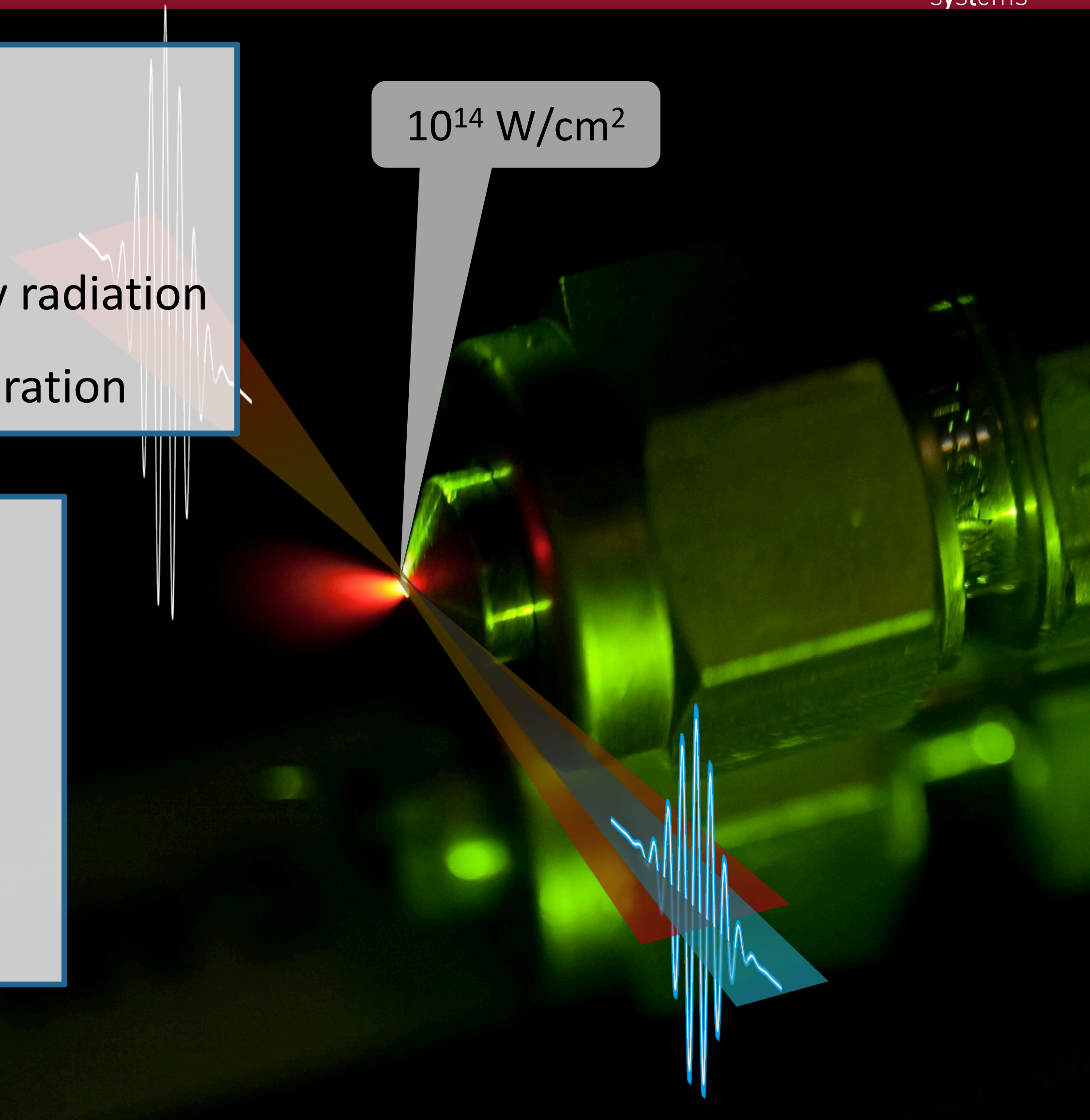
High Harmonic Generation – 3 step model



High Harmonic Generation

- table-top
- coherent (laser-like)
- extreme ultraviolet / soft x-ray radiation
- femto- to attosecond pulse duration



diversity of applications

- surface-science
- atomic/molecular physics
- spectroscopy
- imaging

Outline

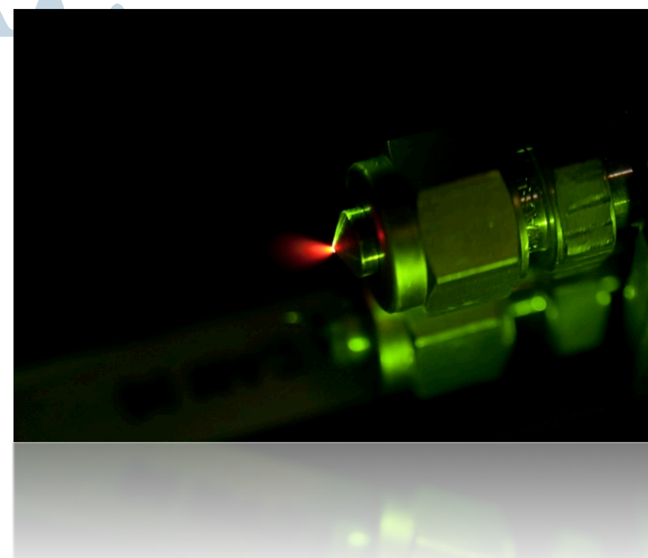
High Harmonic Generation (HHG) – scaling considerations

High average power table-top coherent XUV sources

Applications

Transfer to industrial-grade sources

Summary and Outlook



High Harmonic Generation –scaling considerations

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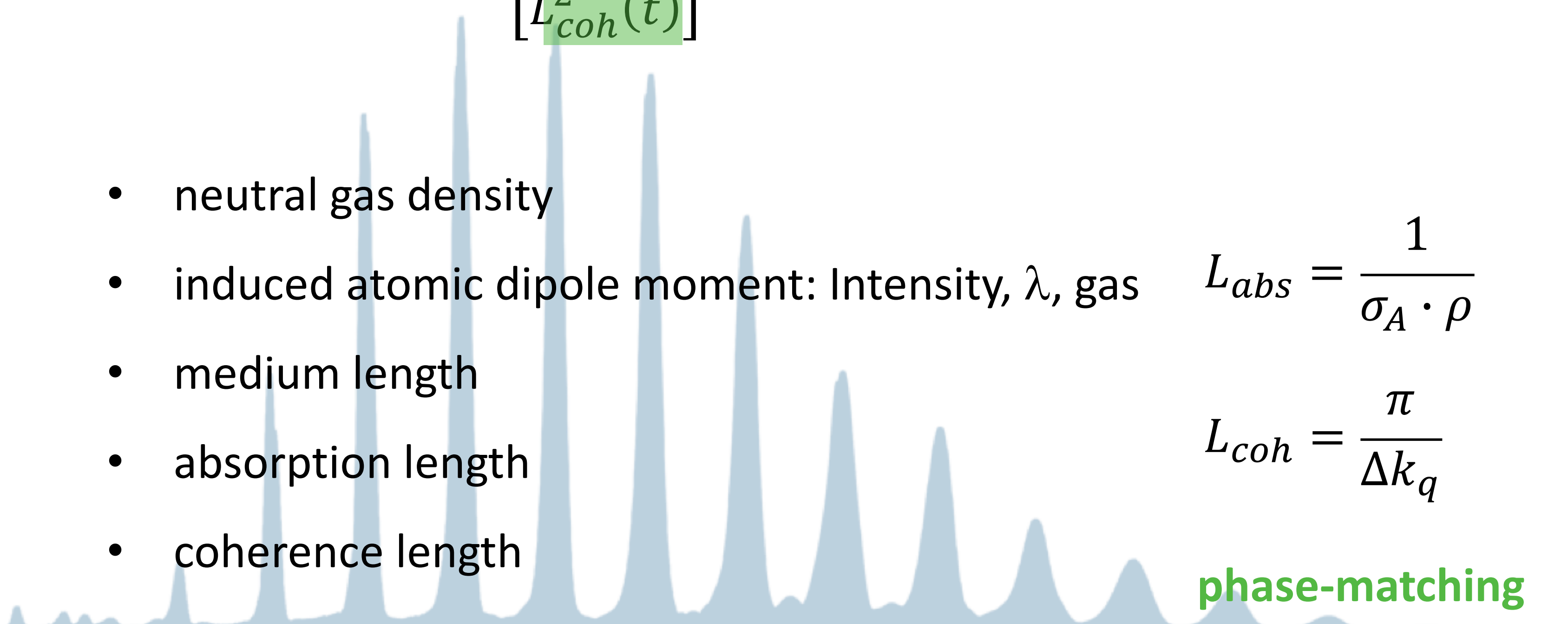
instantaneous harmonic signal[1,2,3]

$$P_{HHG}^{q}(t) \sim \frac{4 \cdot L_{abs}^2 \cdot \rho^2 \cdot [1-\eta(t)]^2 \cdot A_q^2(t)}{1 + 4\pi^2 \cdot \left[\frac{L_{abs}^2}{L_{coh}^2(t)}\right]} \cdot \left[1 + e^{-\frac{L_{med}}{L_{abs}}} - 2\cos\left(\pi \frac{L_{med}}{L_{coh}(t)}\right) \cdot e^{-\frac{L_{med}}{2L_{abs}}}\right]$$



- neutral gas density
- induced atomic dipole moment: Intensity, λ, gas
- medium length
- absorption length
- coherence length

$$L_{abs} = \frac{1}{\sigma_A \cdot \rho}$$

$$L_{coh} = \frac{\pi}{\Delta k_q}$$

phase-matching

[1]E. Constant et al. Phys. Rev. Lett. 82, 1668 (1999).
[2]S. Kazamias et al. Phys. Rev. A 83, 063405 (2011).
[3]T. Popmintchev et al. PNAS 106, 10516 (2009).

High Harmonic Generation –scaling considerations

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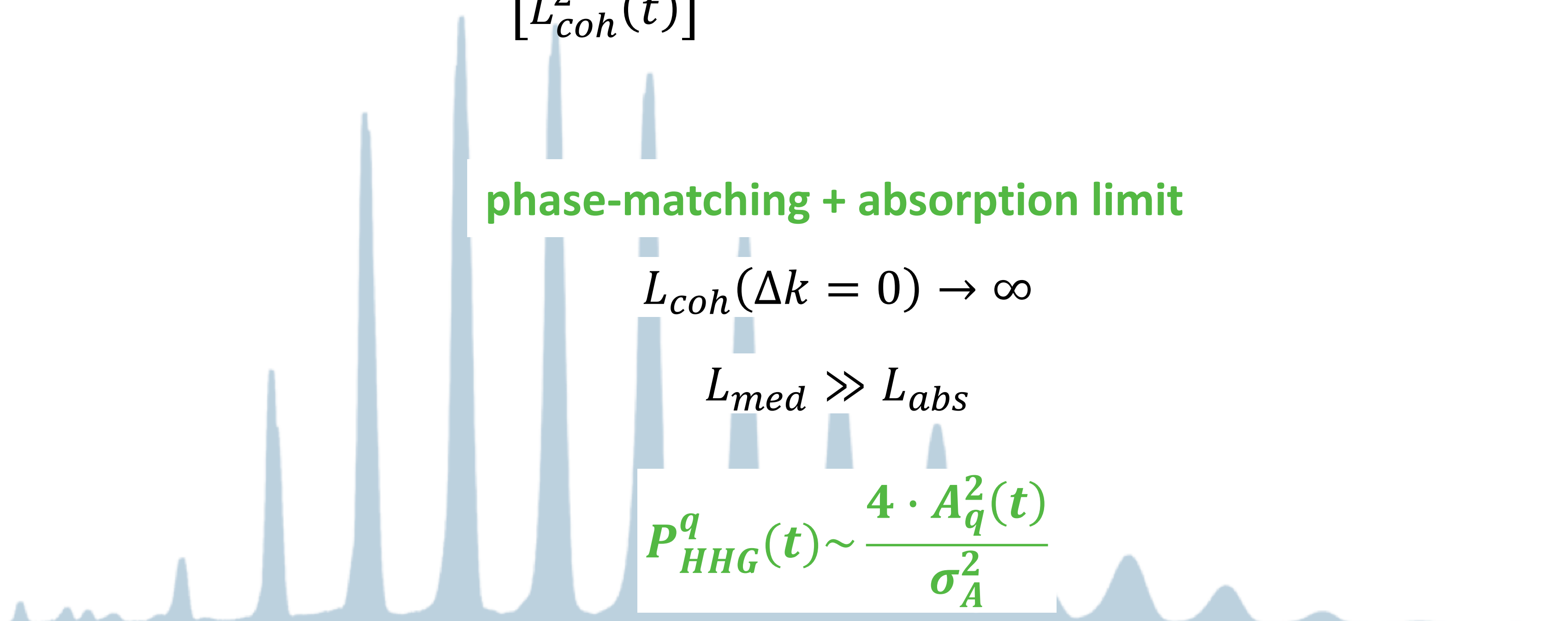


phase-matching + absorption limit

$$L_{coh}(\Delta k = 0) \rightarrow \infty$$

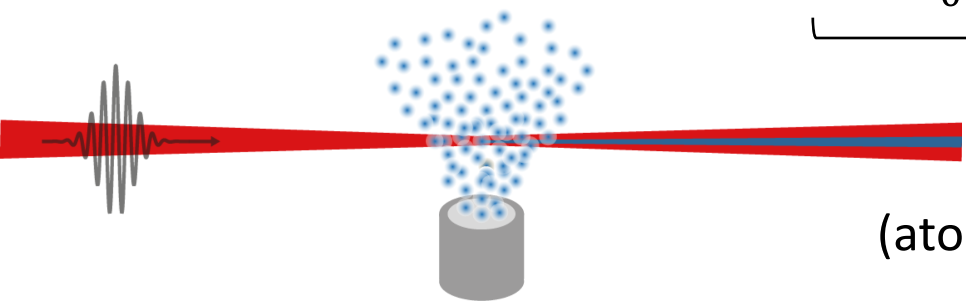
$$L_{med} \gg L_{abs}$$

$$P_{HHG}^{q}(t) \sim \frac{4 \cdot A_{q}^{2}(t)}{\sigma_{A}^{2}}$$

[1]E. Constant et al. Phys. Rev. Lett. 82, 1668 (1999).
[2]S. Kazamias et al. Phys. Rev. A 83, 063405 (2011).
[3]T. Popmintchev et al. PNAS 106, 10516 (2009).

High Harmonic Generation –scaling considerations

$$\Delta k(t,\rho) = q \cdot k_0 - k_q = q \cdot \underbrace{\left(\frac{2\pi}{\lambda_0}\frac{\rho}{\rho_0}\Delta\delta\right) \cdot \left(1 - \frac{\eta(t)}{\eta_{c,q}}\right)}_{+} - \underbrace{\frac{q}{z_R}}_{-}$$



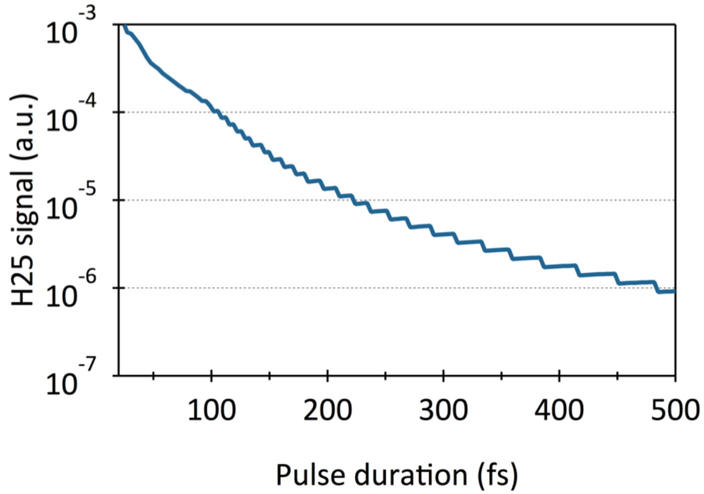
dispersion (atoms, free electrons)

focusing

- density (pressure) dependent
- η_c – critical ionization (gas specific)
- $\eta<\eta_c$: pressure tuned phase-matching
- efficiency **independent** of focusing conditions

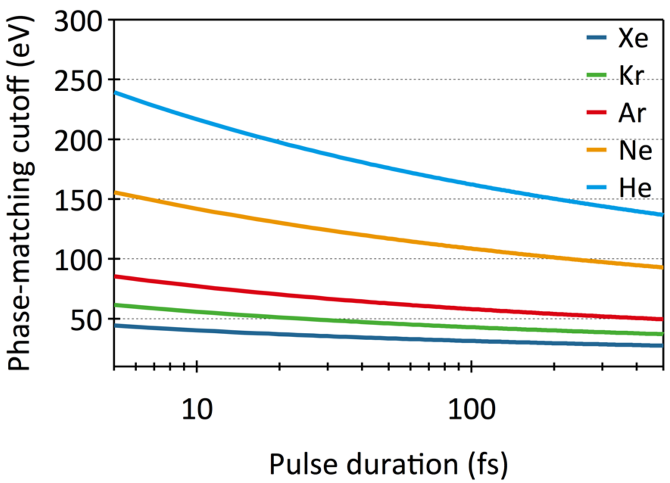
[1]C. Heyl et al. Journal of Physics B **45**, 074020 (2012)
[2]J. Rothhardt et al. New J. Phys. **16**, 033022 (2014)
[3]C. Heyl et al. Optica **3**, 75 (2016)

High Harmonic Generation –scaling considerations

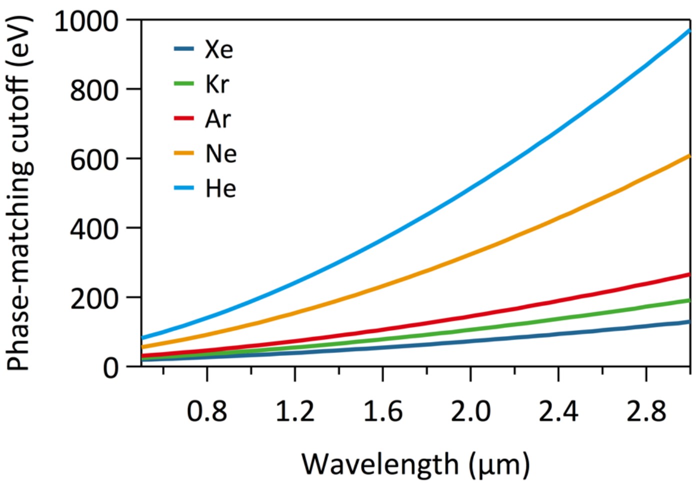


- single atom response ~$I^{8\text{-}9}$
- cutoff increases

$$\hbar\omega_c = I_P + 3.17 \cdot \underbrace{U_p}_{\propto I\cdot\lambda^2}$$



S. Hädrich et al. J. Phys. B. **49**, 172002 (2016).



M. C. Chen et al. Phys. Rev. Lett. **105**, 173901 (2010)
T. Popmintchev et al. Science **336**, 1287 (2012)

High Harmonic Generation –scaling considerations

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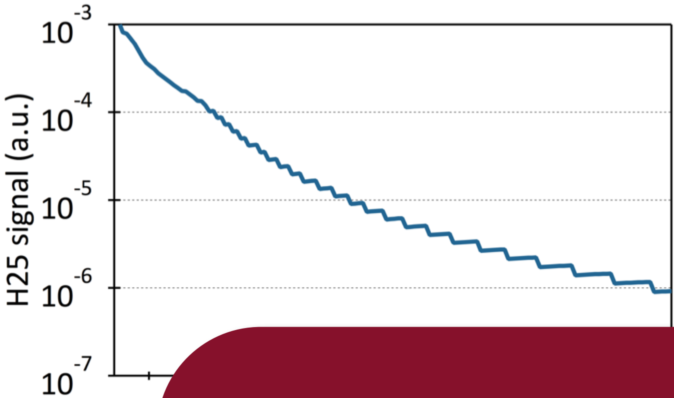
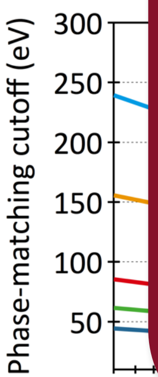


- single atom response ~I$^{8-9}$
- cutoff increases

Phase-matched HHG with fiber lasers

- **tight focusing: no effect on efficiency**
- **high average power ultrashort pulses required**



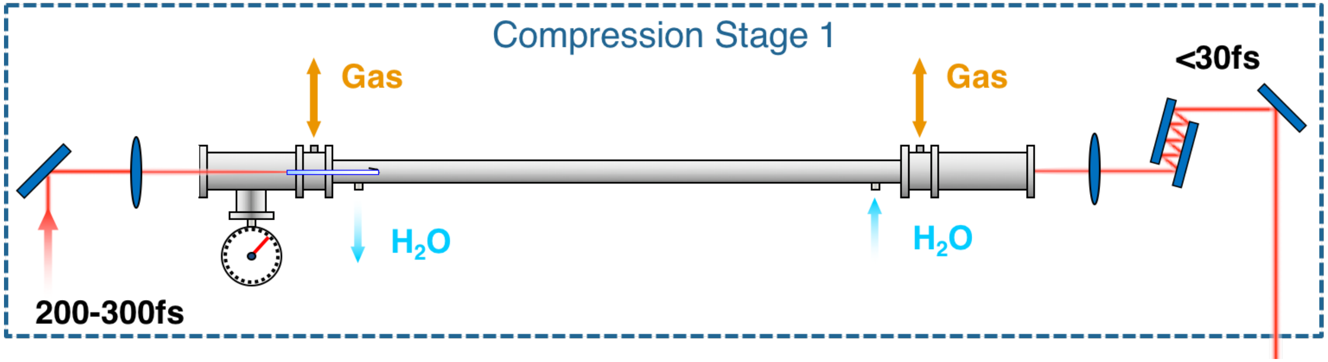
Pulse duration (fs)

Wavelength (µm)

S. Hädrich et al. J. Phys. B. **49**, 172002 (2016).

M. C. Chen et al. Phys. Rev. Lett. **105**, 173901 (2010)
T. Popmintchev et al. Science **336**, 1287 (2012)

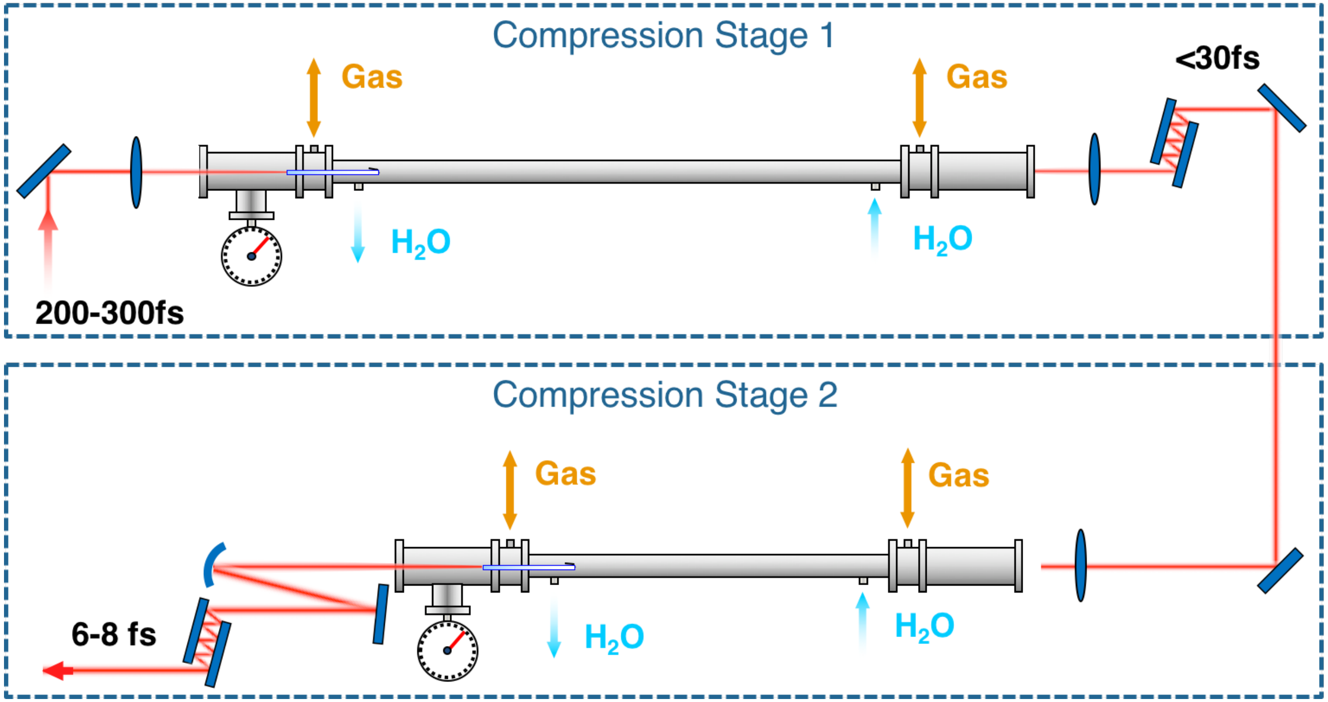
Nonlinear compression



- Ytterbium doped fiber lasers: ~300fs pulses
- Nonlinear-compression in noble-gas filled hollow waveguides
- Sub-30fs with up to 400W average power[1]
- very flexible pulse parameters possible
- average power scalable[2]

[1]S. Hädrich et al. Opt. Lett. **41**, 4332 (2016)
[2]S. Hädrich et al. Appl. Opt. **55**, 1636 (2016)

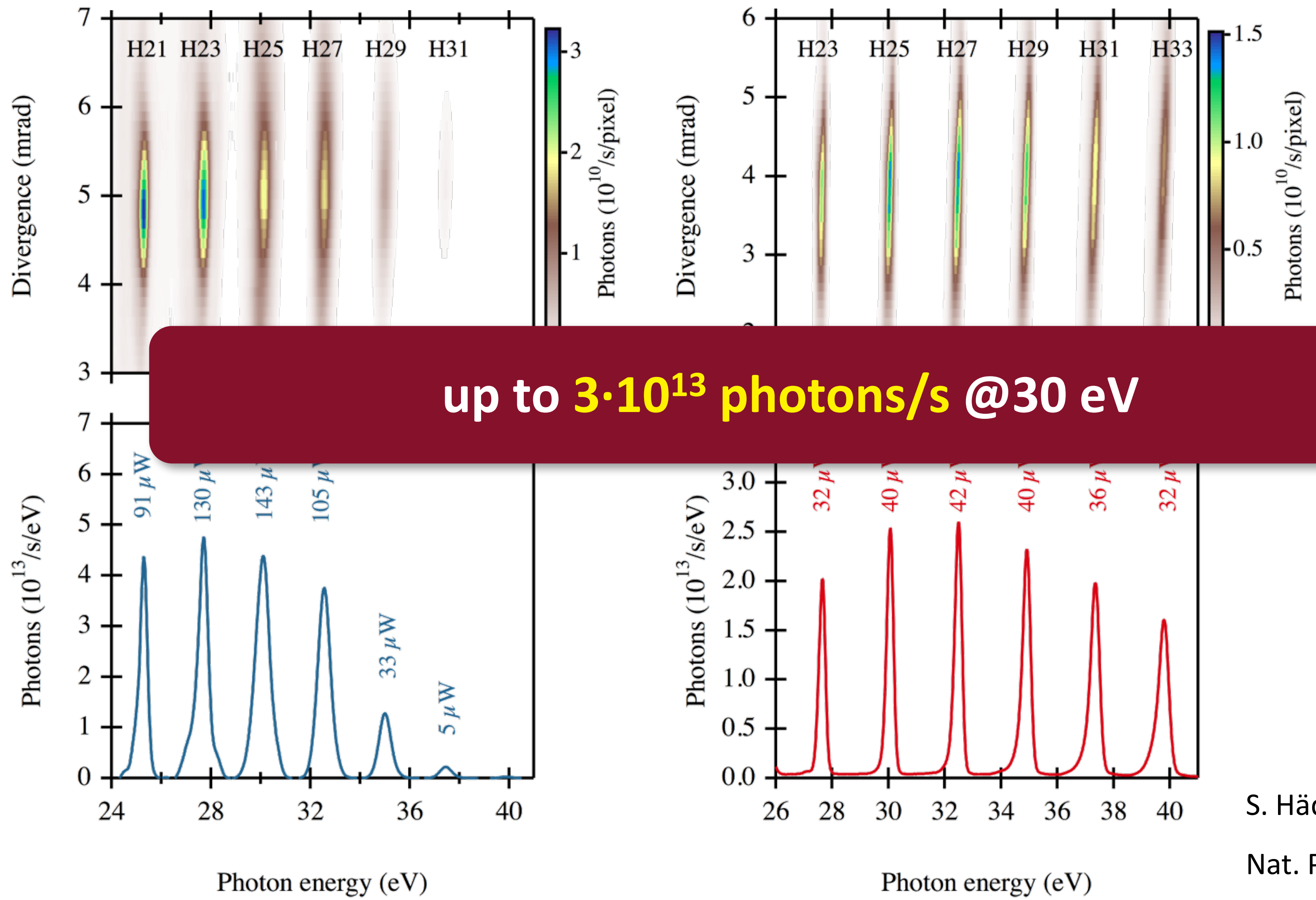
Nonlinear compression



- further pulse compression
- sub-7fs (2 cycle) with up to 216W average power[1]

[1]S. Hädrich et al. Opt. Lett. **41**, 4332 (2016)

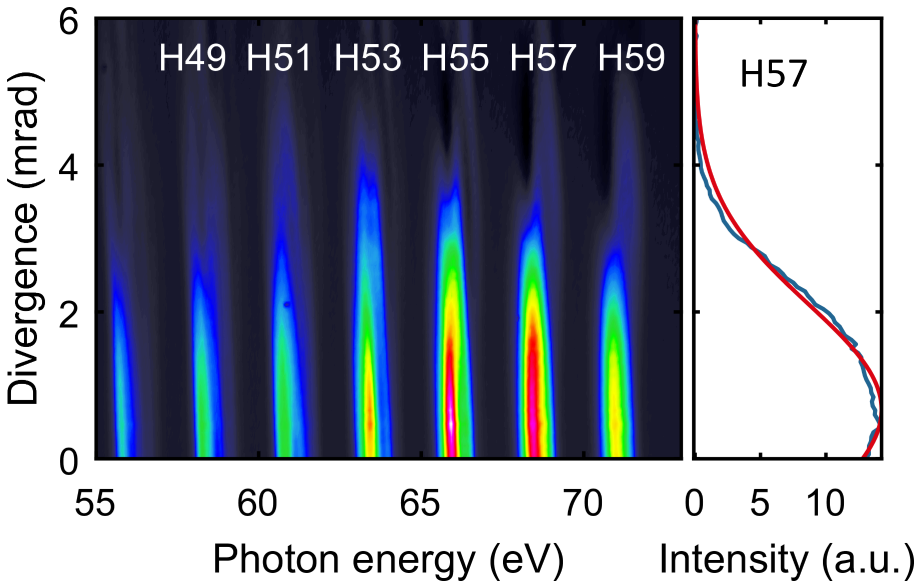
High average power table-top coherent XUV sources

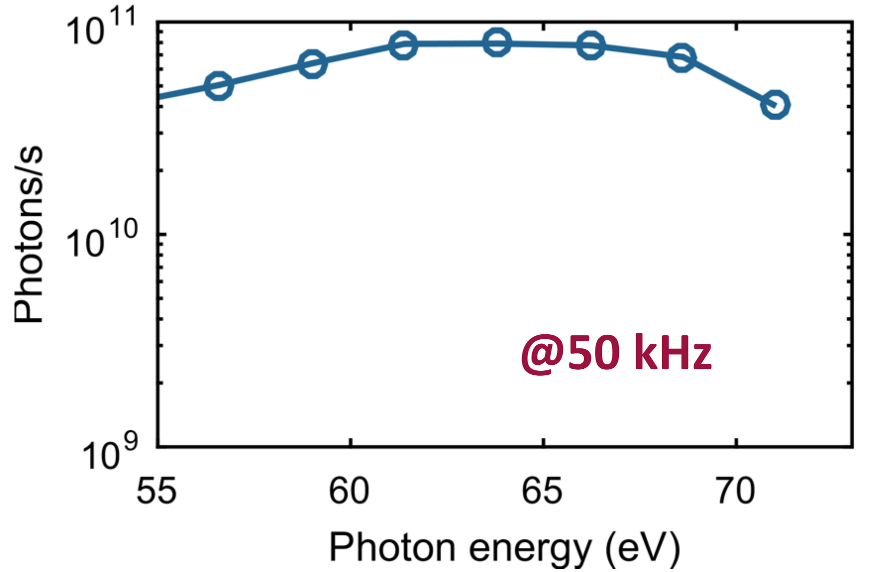


up to 3·10^13 photons/s @30 eV

S. Hädrich et al., Nat. Photon. **8**, 779 (2014).

High average power table-top coherent XUV sources



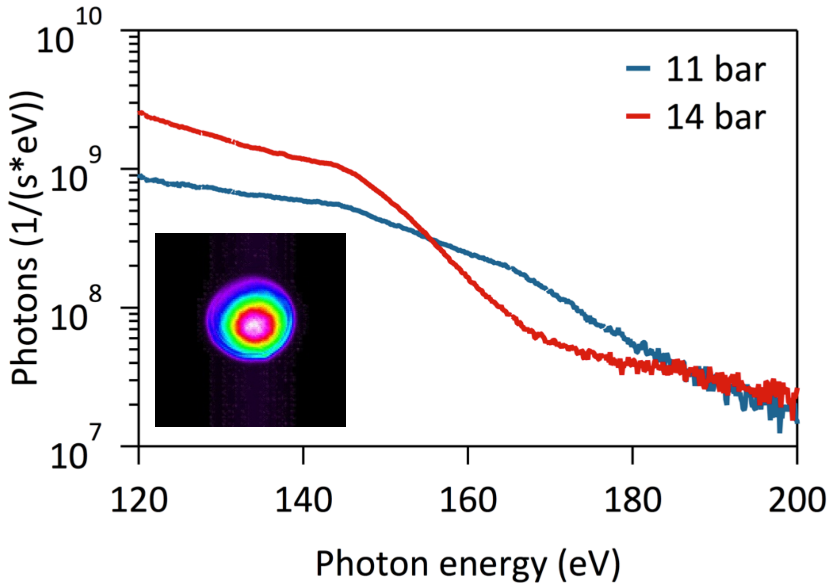


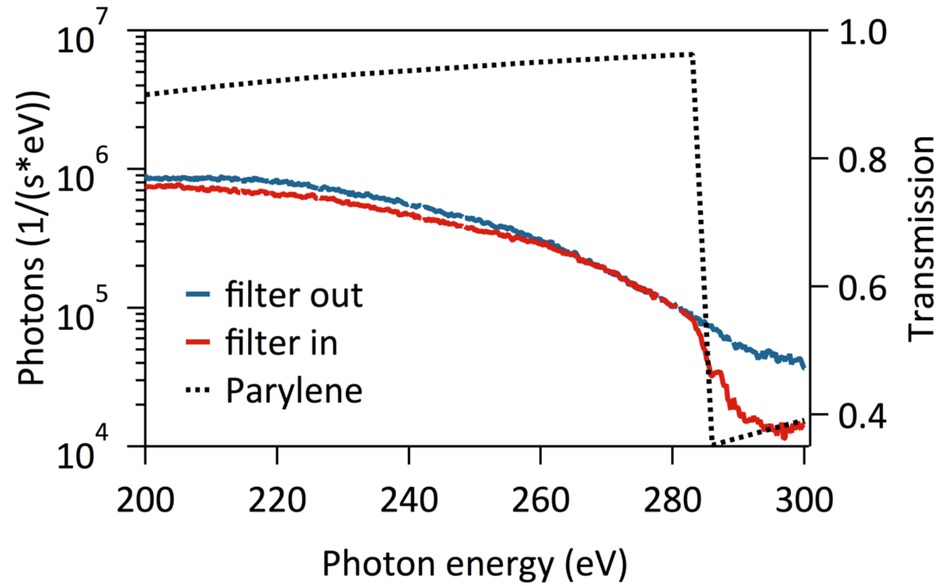
Harmonic	47	49	51	53	55	57	59
Photon energy	56.6	59.0	61.4	63.8	66.2	68.6	71.0
Photons/s (10^{10})	5.0	6.4	7.9	7.9	7.8	6.8	4.0

J.Rothhardt et al., Opt. Express. **24**, 18133 (2016).

High average power table-top coherent XUV sources

@0.1 MHz





- $>10^9$ photons/s up to 150 eV

- water window harmonics
  - $>10^6$ photons/s

J.Rothhardt et al., Opt. Lett. **39**, 5224 (2014).

High average power table-top coherent XUV sources

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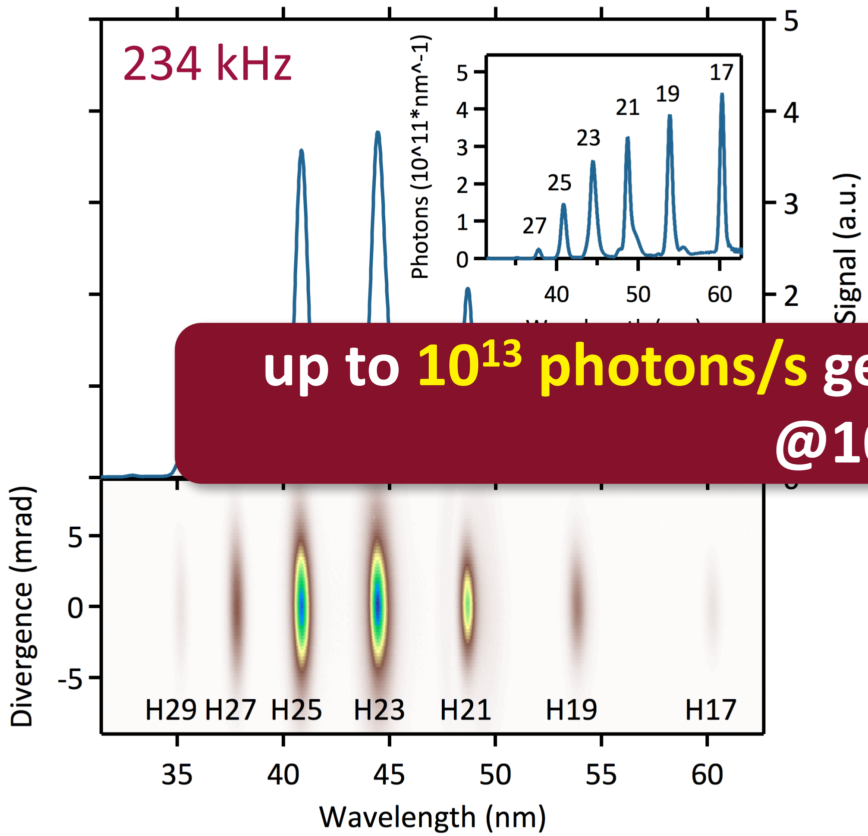
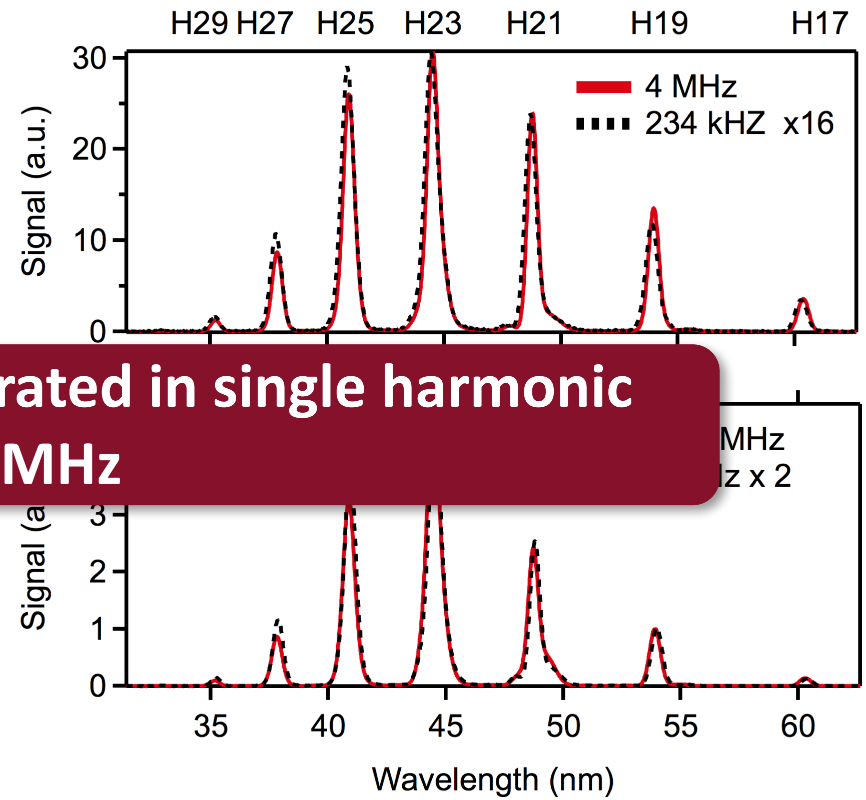




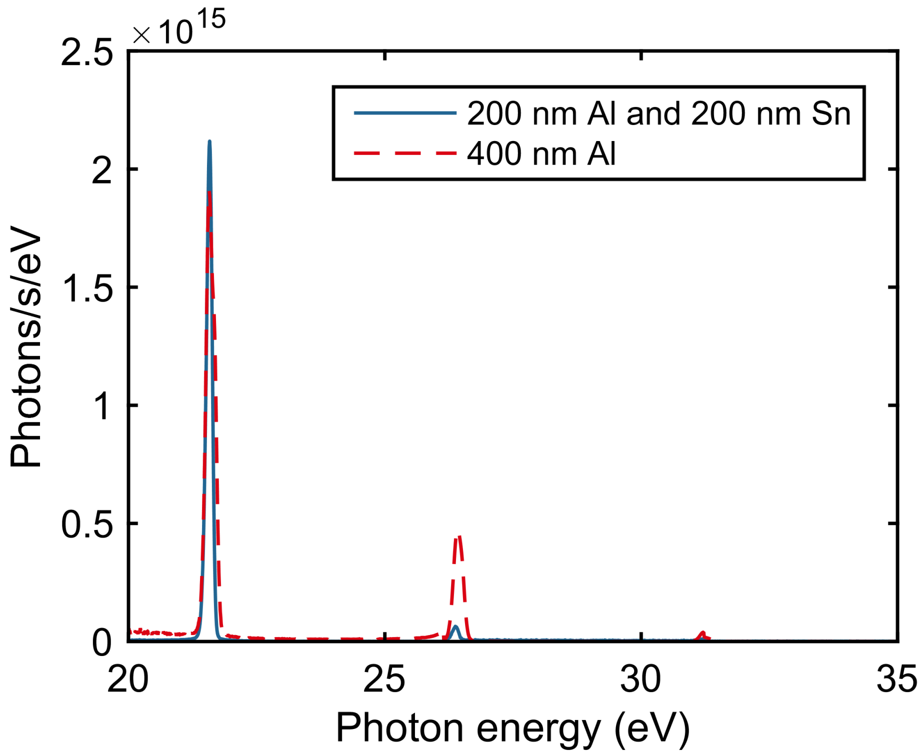
up to 10^{13} photons/s generated in single harmonic @10.7 MHz

	H17	H19	H21	H23	H25	H27	H29
Power (µW) @10MHz	27	35	39	51	25	4	0.4

S. Hädrich et al. Light **4**, e320 (2015); doi: 10.1038/lsa.2015.93

High average power table-top coherent XUV sources

SHG of nonlinear compressed pulses



Calculation of generated photon flux:

- (1500 ± 600) µW @ 21.7 eV
- $4.4 \cdot 10^{14}$ Photons per second

Additional measurement with calibrated photo diode:

- (832 ± 204) µW @ 21.7 eV
- $2.5 \cdot 10^{14}$ Photons per second

Energy contained in small bandwidth:

- $\Delta E/E \sim 9.8 \cdot 10^{-3}$

R. Klas et al., Optica **3**,1167 (2016).

High average power table-top coherent XUV sources

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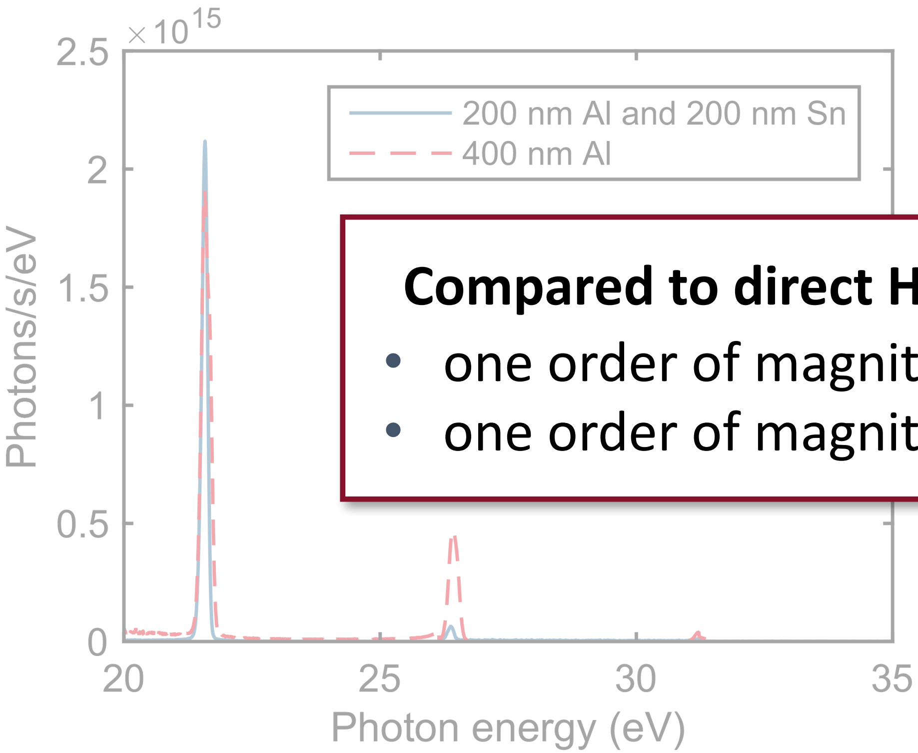
SHG of nonlinear compressed pulses



Compared to direct HHG:

- one order of magnitude higher flux
- one order of magnitude smaller bandwidth

Calculation of generated photon flux:

- $(1500 \pm 600)\ \mu W$ @ 21.7 eV
- second

with

- $(832 \pm 204)\ \mu W$ @ 21.7 eV
- $2.5 \cdot 10^{14}$ Photons per second

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R. Klas et al., Optica **3**,1167 (2016).

State-of-the-art in HHG

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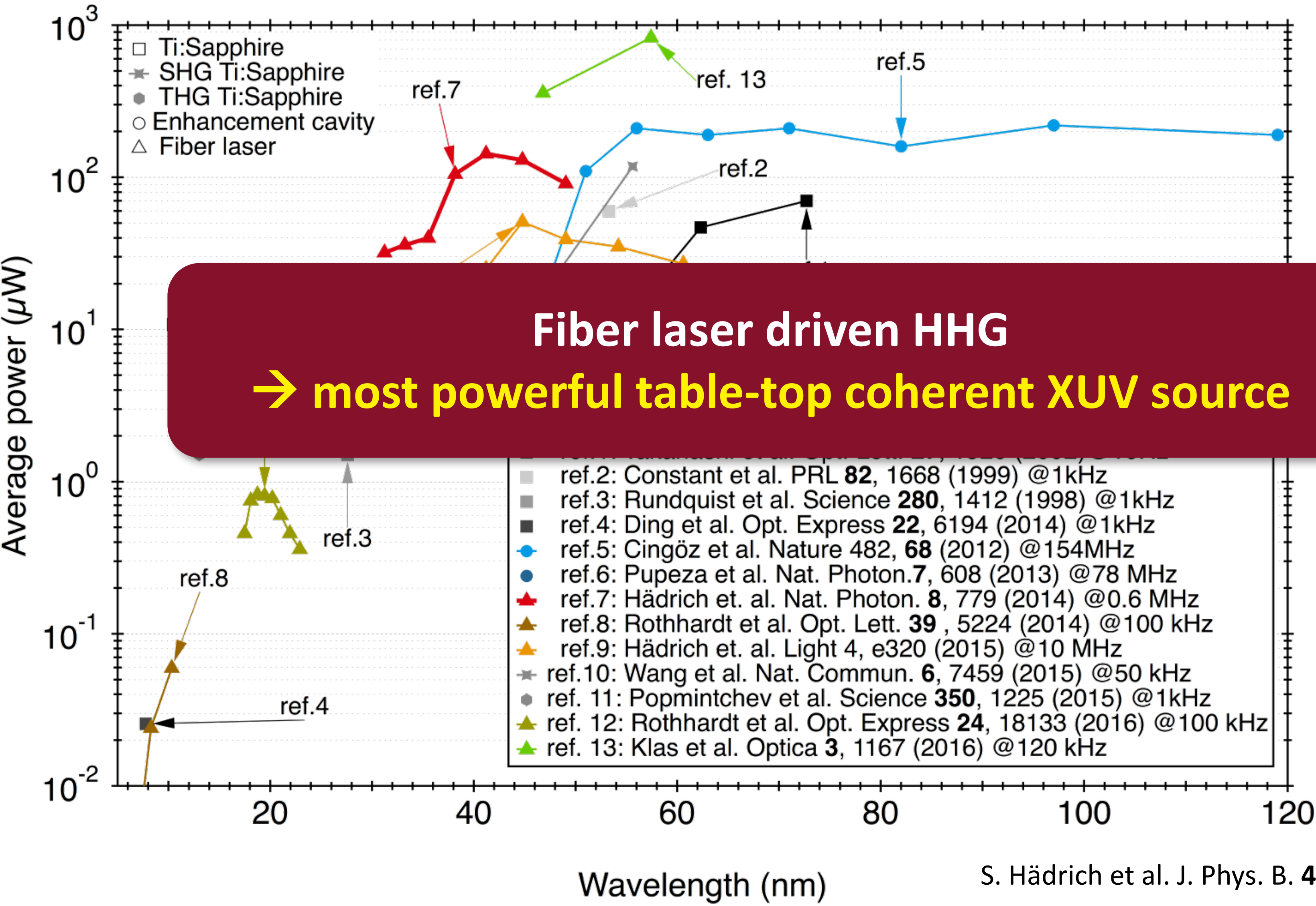
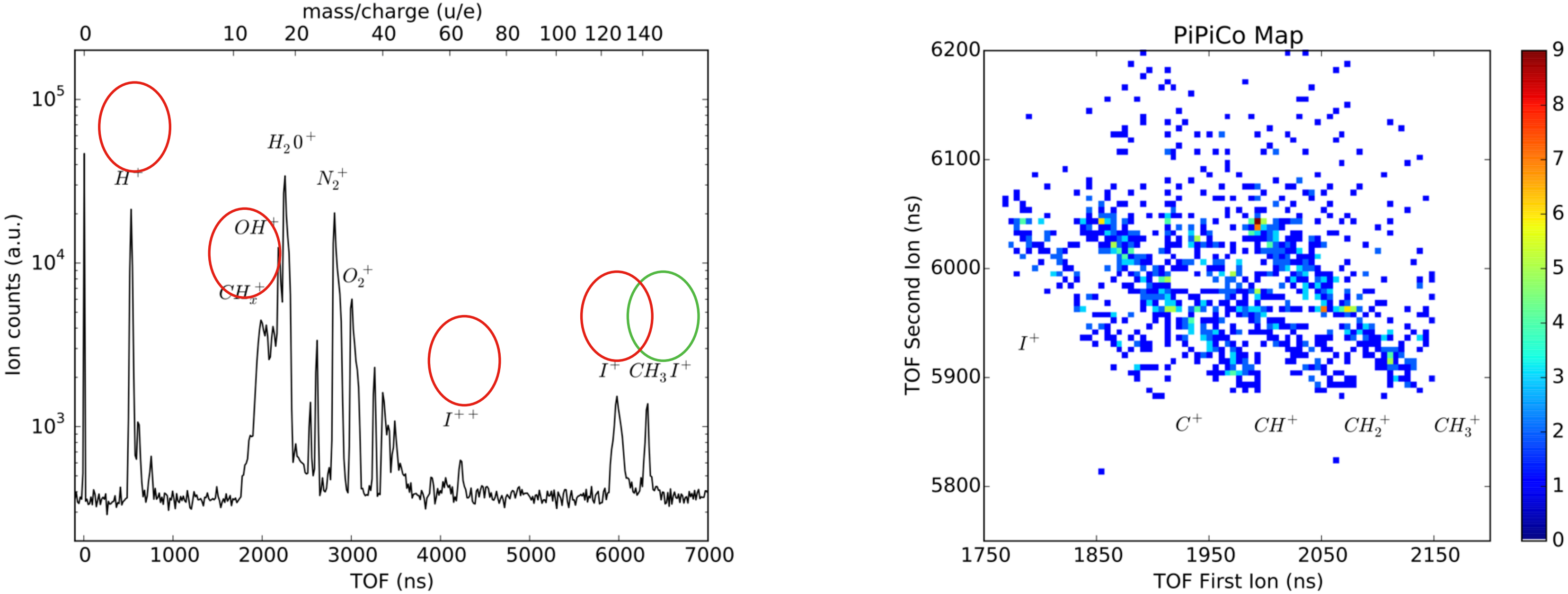


Fiber laser driven HHG

→ most powerful table-top coherent XUV source

S. Hädrich et al. J. Phys. B. **49**, 172002 (2016).

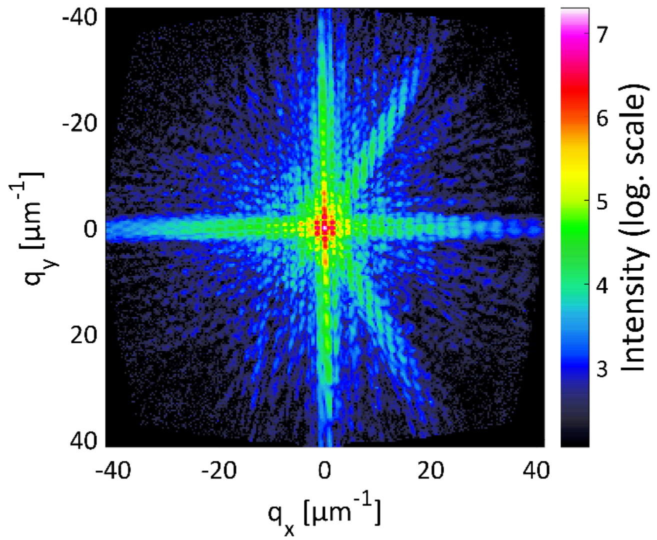
Applications: coincidence measurement



first coincidence measurement
on inner-shell ionized gas-phase molecules
→ table-top sources
→ Promising for time-resolved experiments

J.Rothhardt et al., Opt. Express. **24**, 18133 (2016).

Applications: coherent diffractive imaging

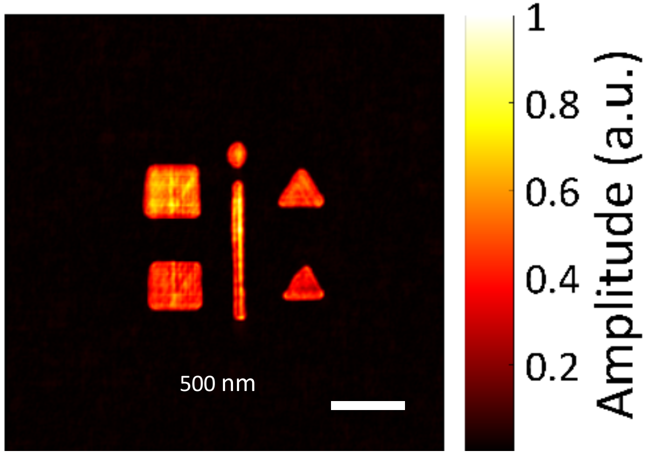


- Diffraction at NA = 0.7

→ Abbe limit of 12 nm

→ Merged together numerically for higher dynamic range.

- Object faithfully reconstructed
- Cross-section reveals a 10% - 90% half-pitch **resolution of 13nm**
- Highest resolution for a table-top XUV/X-ray microscope.



G. Tadesse et al. Opt. Letters **41**, 5170 (2016)

Transfer to industrial-grade sources

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Founded in 2009 : spin-off from the Institute of Applied Physics of Friedrich-Schiller Universität Jena and the Fraunhofer IOF, Jena

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Transfer to industrial-grade sources

Founded in 2009 : spin-off from the Institute of Applied Physics of Friedrich-Schiller Universität Jena and the Fraunhofer IOF, Jena

- Idea: transfer of outstanding laser parameters available in the university labs to compact, robust and reliable commercial laser systems
- Today technological leader for high-power ultrafast fiber lasers
- Focus on scientific market, laser systems adapted to the customer's application

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Fraunhofer IOF

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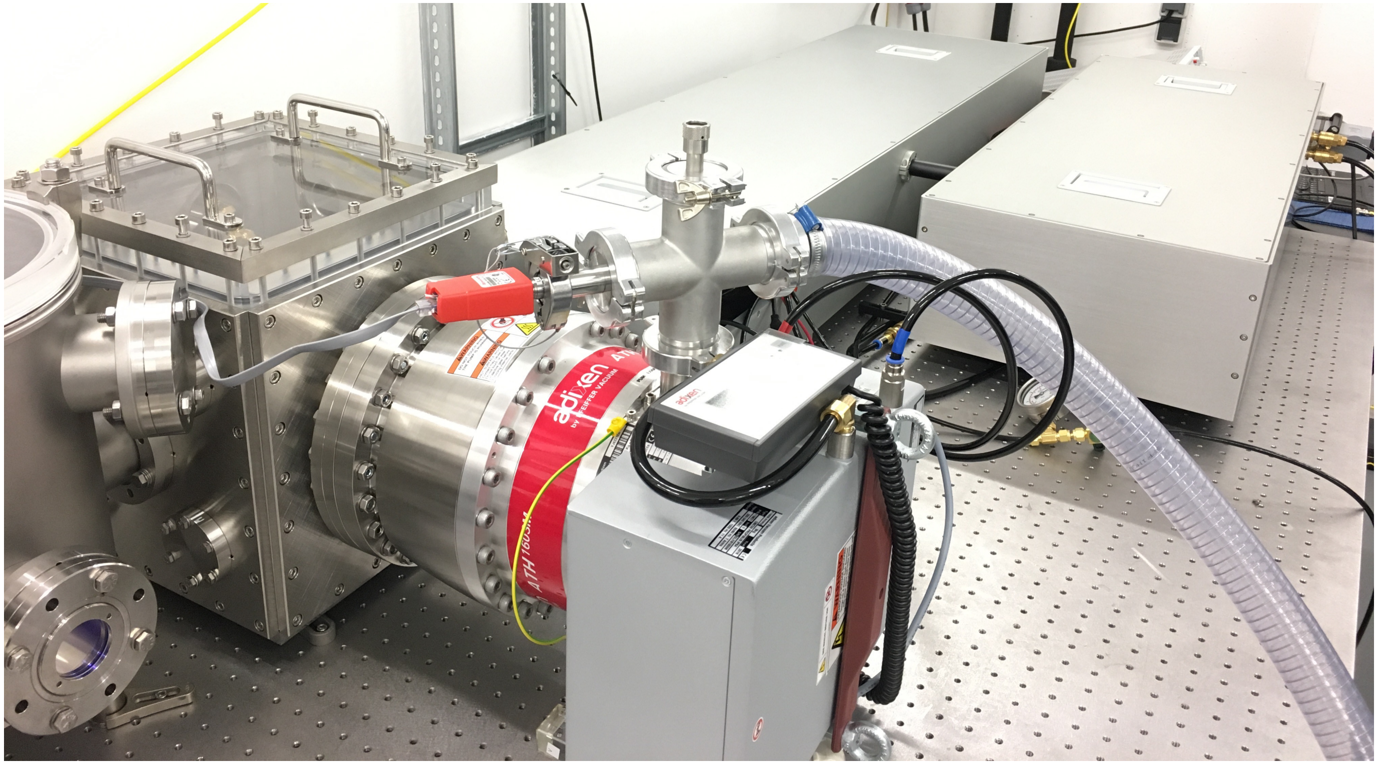
Transfer to industrial-grade sources

- Compact 100W/200µJ turnkey femtosecond laser
- All parameters software controlled
- Alignment-free operation
- Single-mode output beam
- Adjustable pulse length from 350fs to 10ps
- Repetition rate: 50kHz … 20MHz
- Dust sealed, temperature-stabilized housing
- Average-power stability: <0.2% RMS, energy stability: <0.8% RMS

Transfer to industrial-grade sources

- Nonlinear compression: 50W / 100µJ /30 fs
- Second Harmonic Generation
- Dual-beam (IR+ SHG) high repetition rate HHG beamline @500kHz
- Flexible HHG parameter
- High photon flux
- Compact design



Summary and outlook

activefiber systems

- High average power fiber lasers + nonlinear compression

→ Flexible and scalable, ultrashort pulse driver for HHG

→ >400W, 30 fs pulses

→ >200W, sub-2 cycle pulses

- HHG with fiber lasers

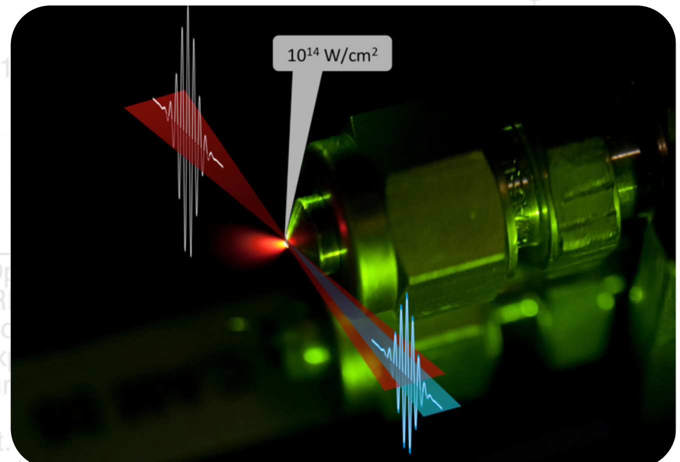
→ up to 10 MHz repetition rate

→ mW level in single harmonic

→ narrowband / broadband

→ application proven

→ transferred to industrial grade sources



S. Hädrich et al. J. Phys. B. **49**, 172002 (2016).

Thank you for your attention.

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